GJO–HGLP–1.7.1
Revision 0

Hanford 200 Areas Spectral Gamma Baseline Characterization Project

Baseline Characterization Plan

December 2002

U.S. Department of Energy

GRAND JUNCTION OFFICE

Work Performed Under DOE Contract No. DE–AC13–02GJ79491 for the U.S. Department of Energy
Approved for public release; distribution is unlimited.

GJO-HGLP 1.7.1
Revision 0

Hanford 200 Areas Spectral Gamma Baseline Characterization Project

Baseline Characterization Plan

December 2002

Prepared for
U.S. Department of Energy
Grand Junction Office
Grand Junction, Colorado

Prepared by
S.M. Stoller Corp.
Grand Junction Office
Grand Junction, Colorado

Work performed under DOE Contract No. DE–AC13–02GJ79491.

Contents

	Page
Signature Page	iv
1.0 Introduction	1
2.0 Background	1
3.0 Purpose and Scope	2
4.0 Organization and Responsibility	3
4.1 DOE-RL	3
4.2 DOE-GJO	3
4.3 Stoller	3
4.3.1 Hanford Office Project Manager	3
4.3.2 Technical Lead	4
4.3.3 Hanford Project Coordinator	4
4.4 Fluor Hanford, Inc. (FH)	4
4.5 Groundwater Protection Program	4
4.6 Pacific Northwest National Laboratories (PNNL)	4
4.7 Key Personnel	5
5.0 Characterization Database	6
6.0 Selection of Boreholes for Characterization	6
7.0 Data Acquisition	7
8.0 Data Processing and Evaluation	8
9.0 Data Reporting	8
10.0 Routine Reports	10
11.0 References	10

List of Figures

Figure 5-1. Borehole Proximity Codes 6

Contents (con't.)

Page

List of Tables

Table 4-1. Key Personnel for the Hanford 200 Areas Spectral Gamma Baseline Characterization Project 5

Appendix A. Gamma Energy and Yield Values for Prominent Gamma Lines Associated with Selected Radionuclides A-1

Hanford 200 Areas Spectral Gamma Baseline Characterization Project
Baseline Characterization Plan

Prepared by:

Richard G. McCain, Technical Lead
S.M. Stoller Corp., Hanford

Dec 10, 2002
Date

Approved by:

Michael C. Butherus, Program Manager
S.M. Stoller Corp., Grand Junction Office

12/11/02
Date

W.D. Steele, Project Manager
S.M. Stoller Corp., Grand Junction Office

12/11/02
Date

John Silko, Program Manager
U.S. Department of Energy
Richland Operations Office

12.13.02
Date

1.0 Introduction

The U.S. Department of Energy Richland Office (DOE-RL) has requested that the DOE Grand Junction Office (DOE-GJO) conduct spectral gamma logging measurements in existing boreholes in the vicinity of waste sites in the Hanford 200 Areas and vicinity. The purpose of this program is to detect and quantify naturally occurring and man-made gamma-emitting radionuclides in the vadose zone in the vicinity of liquid waste disposal sites and solid waste burial grounds. This work scope represents an extension of the baseline characterization work completed in the vicinity of the Hanford single-shell tanks.

As operating contractor for DOE-GJO, S.M. Stoller Corporation (Stoller) is responsible for performing this task. The existing high-resolution spectral gamma logging system (SGLS) developed by Stoller for use in steel-cased boreholes will be used to collect data in the vicinity of liquid waste disposal sites. When the activity rate indicates high concentrations of man-made radionuclides, it may also be necessary to employ the high rate logging system (HRLS) to collect data in zones where the gamma flux is too intense for the SGLS.

This document describes the tasks and organizational requirements associated with geophysical logging operations in existing boreholes. Specific tasks included in this work scope include:

- Comparison of reported borehole and casing survey data with field location of borehole and reporting identified discrepancies.
- Development of a database of existing boreholes and associated geophysical log(s) or geological data. The database will identify most boreholes co-located within or adjacent to waste sites.
- Characterization data acquisition (spectral gamma logging of the 200 Area boreholes).
- Data evaluation and reporting.
- Technical support to on-going site characterization, remediation, monitoring, and modeling activities.
- Routine reporting.

The scope of the Hanford 200 Areas Spectral Gamma Baseline Characterization Project includes geophysical logging operations in more than 800 existing cased boreholes in and around the Hanford 200 East and 200 West Areas.

2.0 Background

The 200 Area plateau is the site of chemical processing plants used to separate and recover plutonium and uranium from irradiated reactor fuel elements. In addition to highly radioactive waste stored in underground tanks, processing operations resulted in discharge of approximately 346 billion gallons (1.3 trillion liters) of chemically contaminated, low-activity liquids to the vadose zone in the 200 Areas. Scavenged waste from some high-level waste tanks was also discharged to the vadose zone. Much of this discharge occurred through ponds or engineered drainage structures such as cribs, tile fields, retention trenches, or reverse wells. Additional discharges to the vadose zone resulting from operator error or equipment failure are referred to as unplanned releases.

Burial grounds were established in the 200 Areas where solid wastes generated during Hanford operations in the 200 Areas and radioactive wastes from offsite have been stored. Radioactively contaminated solid waste includes waste generated by the failure or obsolescence of chemical processing equipment; construction and demolition activities; protective clothing, filters, and miscellaneous process related materials; contaminated soil, and other related material. Low-level radioactive solid wastes from other DOE sites and laboratories, universities, the military, and commercial companies involved in government programs are also stored in the burial grounds. Prior to 1980, liquid organic waste was disposed of in the burial grounds.

Numerous cased boreholes exist in and near waste disposal sites. Additional investigations in these boreholes and proposed boreholes are planned. Spectral gamma logging of these boreholes will provide valuable information regarding the nature and extent of vadose zone contamination associated with gamma-emitting radionuclides. Variations in naturally occurring radionuclides (^{40}K, ^{238}U, and ^{232}Th) are also useful in stratigraphic correlation. Both the 200 East and 200 West Areas contain tank farms and liquid waste sites in close proximity to each other. The key geophysical characterization data provided by this program will result in a more complete definition of subsurface contaminant plumes and correlation of potential contaminant source(s) with preferential contaminant migration pathways through the vadose zone into groundwater and preclude subsequent unsound environmental management decisions.

3.0 Purpose and Scope

The purpose of the Hanford 200 Areas Spectral Gamma Baseline Characterization Project is to collect spectral gamma data from existing boreholes in the Hanford 200 Areas. Data will be collected using program-dedicated equipment and defensible methodology. The primary goal is to extend the existing baseline data set associated with the Hanford single-shell tank farms into the surrounding areas occupied by liquid and solid waste sites.

Data from each borehole will be analyzed to determine concentrations of naturally occurring radionuclides (^{40}K, ^{232}Th, ^{238}U, and associated decay progeny), as well as man-made gamma-emitting radionculides such as ^{137}Cs, ^{60}Co, and $^{152/154}$Eu.

Specific activities under this project will include preparation and maintenance of a database of existing boreholes and geophysical log data, logging existing boreholes with the spectral gamma logging system and high-rate logging system, analysis and plotting of log data, and preparation of reports. Because many liquid waste sites are currently the subject of site characterization efforts in RI/FS work plans, well logging will be performed in existing and new boreholes within and immediately adjacent to these sites within a time frame suitable to provide data for incorporation into Remedial Investigation Reports.

4.0 Organization and Responsibility

This section defines the organizational roles and responsibilities for the Hanford 200 Areas Spectral Gamma Baseline Characterization Project.

4.1 DOE-RL

DOE-RL is responsible for most of the 200 Areas waste disposal sites and associated facilities. Some of the liquid waste disposal sites associated with tank farms are under control of the DOE Office of River Protection (DOE-ORP). DOE-RL approves the work scope for vadose zone geophysical characterization and provides sufficient and timely funding for assignment to the Stoller contract.

DOE-RL will review and approve deliverables prepared by Stoller to ensure that they meet the requirements of the specific work scope, are consistent with DOE policy and the quality assurance (QA) program, ES&H program, project control programs, and are of high technical quality.

4.2 DOE-GJO

DOE-GJO is responsible for geophysical logging activities. DOE-GJO authorizes its contractor, Stoller, to perform the approved work scope and provides appropriate direction to Stoller to initiate approved tasks consistent with assigned funding.

4.3 Stoller

As the GJO contractor, Stoller, through its offices in Grand Junction, Colorado, and Richland, Washington, is responsible for project management, planning, cost account management, equipment maintenance and calibration, logging operations, data management, data analysis and plotting, report preparation, and technical support to DOE-RL.

4.3.1 Hanford Office Project Manager

The project manager is responsible for managing project activities and reporting project status and changes to the program manager and the DOE project managers. The project manager directs project activities within authorized funding and approved scope and schedule and is responsible for cost and schedule control. The project manager reviews and approves all project plans, procedures, reports, and deliverables.

4.3.2 Technical Lead

The Hanford technical lead is responsible for the overall technical direction of the project. This includes review and approval of technical documents, including plans, procedures, and characterization reports.

The GJO technical lead provides technical support to the Hanford office in the area of borehole geophysical logging. The GJO technical lead also analyzes calibration data and prepares the annual calibration report.

4.3.3 Hanford Project Coordinator

The project coordinator is responsible for the coordination and direction of characterization activities. The project coordinator works with Hanford Site contractor personnel to schedule field activities and supports the project manager in budgeting, tracking, and reporting of project activities.

4.4 Fluor Hanford, Inc. (FH)

As the Hanford Site contractor responsible for environmental investigation and remediation, FH is responsible for providing site access and support services, including operator and health physics technician support as required for characterization activities at liquid waste disposal sites. FH will provide existing training courses and facilities, as needed, to meet site-specific entrance and operating requirements for Stoller personnel.

FH is also responsible for installation of groundwater monitoring wells under supervision of Pacific Northwest National Laboratories (PNNL). FH drilling coordinators will keep Stoller informed of the progress of the site characterization and groundwater monitoring well drilling efforts so that logging services can be provided on a timely basis.

4.5 Groundwater Protection Program

The Groundwater Protection Program is responsible for integrating all Hanford Site groundwater/vadose-zone-related work scope. The Hanford 200 Areas Spectral Baseline Characterization Project data should be used by the Tank Farms Vadose Zone Project and the System Assessment Capability, the Groundwater Monitoring and Modeling, the Waste Site Groupings' RI/FS(s), the Applied Science and Technology, and the immobilized low-activity waste (ILAW) programs. When informed of the various projects' data needs, the Hanford 200 Areas Spectral Gamma Baseline Characterization Project will adjust its data collection activities to meet the needs of the other projects, as directed by DOE-RL.

4.6 Pacific Northwest National Laboratories (PNNL)

During this characterization project, groundwater monitoring wells will be installed under the direction of the PNNL groundwater monitoring group to satisfy groundwater monitoring requirements under the Resource Conservation and Recovery Act (RCRA). These RCRA groundwater monitoring wells will be logged by Stoller during installation. PNNL is responsible for geologic evaluation of the log data and final well construction recommendations. PNNL will be responsible for informing Stoller personnel of status of the borehole drilling and providing sufficient time at the wellhead for log acquisition.

4.7 Key Personnel

Key personnel involved in the Hanford 200 Areas Spectral Gamma Baseline Characterization Project are listed in Table 4-1.

Table 4-1. Key Personnel for the Hanford 200 Areas Spectral Gamma Baseline Characterization Project

Title	Name	Telephone Number
DOE-RL		
Project Manager/COR/TOM	John Silko	(509) 373-9876
Stoller		
Program Manager	Mike Butherus	(970) 248-6332
Project Manager	Doug Steele	(970) 248-6703
Technical Lead (Hanford)	Rick McCain	(509) 376-6435
Technical Lead (GJO)	Carl Koizumi	(970) 248-7797
Project Coordinator	Steve Kos	(509) 376-6432 (office) (509) 539-9497 (cellular)
Records Coordinator	Rachel Paxton	(509) 376-6437
Office Administrator	Jill Meinecke	(509) 376-6454
Fluor Hanford, Inc. (FH)		
Manager, Waste Site Remedial Actions	Bruce Ford	(509) 373-3809
Pacific Northwest National Laboratories (PNNL)		
Applied Geology and Geochemistry	Duane Horton	(509) 376-6868

5.0 Characterization Database

A database of existing boreholes in and near the Hanford 200 Areas has been developed to facilitate planning and scheduling characterization of characterization activities. The database also contains references to existing logs and other pertinent data. Whenever possible, boreholes are associated with specific waste sites. A "proximity code" has been included to indicate the relationship between a borehole and its associated waste site. The proximity codes are defined as follows:

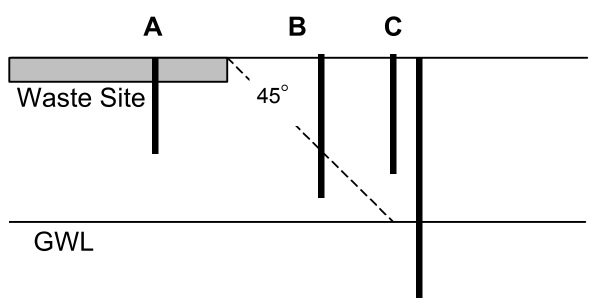
A. The borehole is located within the perimeter of the associated waste site.

B. The borehole is located outside the perimeter of the waste site, but intersects the volume in the vadose zone defined by a line extending outward from the perimeter of the vadose zone at an angle of 45 degrees from the vertical. (In general, this means that the depth of the borehole is greater than the distance from the perimeter.)

C. The borehole is located outside the perimeter of the waste site and does not intersect the vadose zone volume defined above. (In general, this means that the depth of the borehole is less than the distance from the perimeter, or that the depth to groundwater is less than the distance from the perimeter.)

Figure 5-1 illustrates how the proximity codes are defined.

Figure 5-1. Borehole Proximity Codes



6.0 Selection of Boreholes For Characterization

It is intended that all available boreholes will be logged as part of the vadose zone characterization project. Selection of and prioritization of individual boreholes will be based on data needs of Hanford remedial investigation or remediation projects as well as published estimates of waste discharges. All boreholes with a proximity code of A or B will be logged. Boreholes with a proximity code of C will be evaluated on a case-by-case basis. It is possible that boreholes located great distances from waste sites may not be logged, unless the log data may be useful for stratigraphic correlation.

Hanford Site remedial investigation programs currently are based on the analogous site concept, in which specific waste sites are identified as analogs for groups of waste sites with similar characteristics. Under this approach, the majority of the investigative effort takes place at a few sites, and the results are extrapolated to similar waste sites. Vadose zone characterization logging will be performed in about 860 boreholes that are associated with the waste sites in each waste grouping. *Results of spectral gamma logging at all sites will be highly useful for testing the validity of the analogous site concept*. In addition, the logging of existing boreholes will provide information on each waste site that would be unavailable without the installation of additional new boreholes.

For planning purposes, existing boreholes in the 200 Areas have been evaluated in terms of proximity to waste sites, waste site disposal history, waste site location, and relevance to near-term characterization efforts in the ongoing RI/FS process. The schedule will be updated to fulfill the needs of the ongoing RI/FS characterization activities as necessary and the installation of new RCRA groundwater monitoring wells. Prior to logging, any existing logs will be reviewed to assess subsurface conditions and probable contaminant levels. In cases where high quality log data comparable to SGLS data have been recently collected, it may not be necessary to log the borehole again.

7.0 Data Acquisition

Spectral gamma logging data for waste site characterization will be acquired using the equipment, methods, and procedures previously identified for use in the Hanford Tank Farms Vadose Zone Baseline Characterization Project. Field data collection procedures are described in the *Hanford Geophysical Logging Project Logging System Operating Procedures* (DOE 2003b). Principal borehole geophysical logging activities will be conducted by deploying the SGLS, which uses an HPGe detector with an intrinsic efficiency of 35 percent. However, many of the boreholes are much deeper and exhibit a wider array of casing configurations relative to the tank farms boreholes. To enhance detector capability when deployed in boreholes completed with dual casing or unusually thick casing, longer count times will be required. To expedite logging, the depth increment between spectra is being changed from 0.5 to 1.0 ft. In addition to the SGLS, the Radionuclide Logging System (RLS) has recently become available. This logging system, which uses an HPGe detector with 70-percent efficiency, has been calibrated to the same standards as the SGLS. The RLS will be used to log RCRA wells and in deep boreholes where little or no contamination is anticipated. The HRLS will be available for use in borehole intervals where the gamma flux is too intense for the SGLS to discriminate spectra. For quality assurance purposes, repeat logging will be conducted over intervals of at least 10 ft in at least 10 percent of the boreholes. Repeat logging may also be performed using shorter depth increments, longer counting times, or both, in zones where additional detail is required.

Both the SGLS and the HRLS are calibrated on an annual basis. The most recent calibration results are documented in DOE (2000, 2002). Field verification measurements are made before and after each logging run by inserting the logging sonde into a field verifier assembly that contains a uniform distribution of slightly elevated ^{40}K, ^{232}U, and ^{232}Th. Field verification spectra are used to establish a channel number-to-energy calibration relationship for each log run.

8.0 Data Processing and Evaluation

Individual spectra collected by the SGLS and/or HRLS will be processed in batch mode using *Aptec* SUPERVISOR. Data processing and analysis methods are similar to those used in the Hanford Tank Farms Vadose Zone Baseline Characterization Project. However, some minor changes will be made, which include the elimination of errors associated with the calibration function, dead time, and casing correction function from the calculated measurement errors. While these errors still exist and contribute to the overall measurement accuracy, they do not affect the actual precision, or repeatability of the measurements. In the future, error bars shown on the log plots will reflect only the counting error.

Data processing and evaluation will employ the use of Microsoft *Excel* instead of in-house software (*LogAnal*). *Excel* is more widely available and has much better data analysis capability. The *Excel* file format is also compatible with a wider range of software and can be used to create log plots. *SigmaPlot* will continue to be used for final log plots and for compatibility with previous analysis results.

Finally, the radionuclide data used to compute concentrations have been updated. For the single-shell tank baseline work, radionuclide peak energy and yield values were obtained from Erdtmann and Soyka (1979). Future work will be based on data from Firestone and Shirley (1996). For radionuclides of interest to the vadose zone characterization project, differences in energy and yield values are minor. Hence, differences in the calculated concentrations are not significant, relative to errors associated with counting statistics, calibration, and correction factors. However, Erdtmann and Soyka (1979) is out of print. Firestone and Shirley (1996) is widely available and generally consistent with values obtained from nuclear properties databases on the Internet. Gamma energy values from Firestone and Shirley (1996) have been rounded to two decimal places, which is necessary because the library values for gamma energy must match exactly between *Aptec* spectral analysis software and the in-house data processing software. Appendix A contains a listing of radionuclides commonly encountered in spectral gamma logging, sorted by both isotope and gamma energy level.

9.0 Data Reporting

Logs for individual boreholes will be reported as data evaluation is completed. A borehole log report will contain the following elements:

- <u>Log Data Report</u>. The log data report will provide pertinent borehole details, including borehole location with survey data, casing configuration with last top-of-casing survey data, geologic log (if available), depth to groundwater, borehole notes, logging notes, analysis notes, log plot notes, and a summary and conclusions.

- Gross Gamma and Dead Time Plot. Where available, historical logs may also be plotted for comparison purposes.

- KUT Plots. Plots will be prepared showing the naturally occurring radionuclides ^{40}K, ^{238}U, and ^{232}Th in picocuries per gram. ^{40}K values are based on the peak at 1460.83 keV. ^{238}U values are based on the ^{214}Bi peak at 609.31 keV or 1764.49 keV. ^{232}Th values are based on the ^{208}Tl peak at 2614.53 keV.

- Man-Made Radionuclides. When man-made radionuclides such as ^{137}Cs, ^{60}Co, $^{152/154}$Eu, ^{126}Sn, ^{125}Sb, or $^{235/238}$U are encountered, a separate series of plots will be prepared, showing the concentrations (activities) of each radionuclide in picocuries per gram (pCi/g) as a function of depth. Although uranium also occurs naturally, "man-made" uranium can be identified by detection of peaks such as for ^{234m}Pa at 1001.03 keV. This radionuclide rapidly achieves equilibrium with the parent uranium but the peak has a very low yield and generally is not observed at environmental levels. The primary indicators of ^{235}U are the peaks at 185.71 and 205.31 keV.

- Shape Factor Plots. When appropriate, shape factor analysis may be conducted for limited depth intervals to determine the position of ^{137}Cs or ^{60}Cs relative to the borehole, or to detect the presence of ^{90}Sr.

- Special Plots. Other log plots will be created as necessary. For example, an expanded section may be necessary to show high-rate log data for a limited borehole interval. In addition, it may be necessary to correlate baseline log data with other logs.

The borehole log report, log data, and associated plot files shall be maintained in an *Excel* workbook (*.xls) file. For distribution, the log data report and log plots will be converted to a portable document format (*.pdf) file. Generated by a software program called *Adobe Acrobat*, *.pdf files are cross-platform files that can be read or printed, but not modified using the free *Adobe Acrobat Reader* (available via the Internet at http://www.adobe.com). These files are relatively compact and can be sent via email or downloaded from the project web site located on the Internet at: **http://www.gjo.doe.gov/programs/hanf/htfvz.html**. This report format will make the log data available to the widest possible audience with minimal document preparation cost.

After all boreholes associated with a waste site or group of waste sites have been completed, a summary report will be prepared. This report will consolidate information from the individual borehole log reports and summarize vadose zone contamination conditions. Depending on the level of contamination encountered and the degree of complexity, the summary report may include maps, plan-views, cross-sections, and/or three-dimensional visualizations.

10.0 Routine Reports

Routine reports will be issued on a monthly basis as discussed in the Project Management Plan (DOE 2003c). These informal reports will summarize the logging performed in the reporting period, provide the status of data processing and report activities, and discuss any issues, problems, or concerns relevant to the project.

11.0 References

Bechtel Hanford, Inc. (BHI), 1998. *Hanford Site Atlas*, BHI-01119, Rev. 1, Bechtel Hanford, Inc., Richland, Washington.

Chamness, M.A., and J.K. Merz, 1993. *Hanford Wells*, PNL-8800, prepared by Pacific Northwest Laboratory for the U.S. Department of Energy, Richland, Washington.

Erdtmann, G., and W. Soyka, 1979. *Die Gamma-Linen der Radionuklide*, Verlag Chemie GmbH, Weinheim, Deutschland.

Firestone, R.B., and V.S. Shirley, 1996. *Table of Isotopes, 8th Edition*, John Wiley and Sons, New York.

Horton, D.G., 2000. *Borehole Data Package for Wells 299-E33-334 and 299-E33-335 at Single-Shell Tank Waste Management Area B-BX-BY*, PNNL-13199, Pacific Northwest National Laboratories (PNNL), Richland, Washington.

Horton, D.G., and F.N. Hodges, 1999a. *Borehole Data Package for 1998 Wells Installed at Single-Shell Tank Waste Management T*, PNNL-12125, Pacific Northwest National Laboratories (PNNL), Richland, Washington.

__________, 1999b. *Borehole Data Package for 1998 Wells Installed at Single-Shell Tank Waste Management Area TX-TY*, PNNL-12124, Pacific Northwest National Laboratories (PNNL), Richland, Washington.

__________. 1999c. *Borehole Data Package for 1998 Wells Installed at Single-Shell Tank Waste Management Area U*, PNNL-12126, Pacific Northwest National Laboratories (PNNL), Richland, Washington.

__________, 2000. *Borehole Data Package for Well 299-W15-41 at Single-Shell Tank Waste Management Area TX-TY*, PNNL-13201, Pacific Northwest National Laboratories (PNNL), Richland, Washington.

Horton, D.G., and V.G. Johnson, 2000. *Borehole Data Package for Wells 299-W22-48, 299-W22-49, and 299-W22-50 at Single-Shell Tank Waste Management Area S-SX*, PNNL-13200, Pacific Northwest National Laboratories (PNNL), Richland, Washington.

Horton, D.G., and S.M. Narbutovskih, 1999. *Borehole Data Package for Well 299-E33-44 at Single-Shell Tank Waste Management Area B-BX-BY*, PNNL-12128, Pacific Northwest National Laboratories (PNNL), Richland, Washington.

Horton, D.G., and B.A. Williams, 1999. *Borehole Data Package for 216-U-12 Crib Well 299-W22-79*, PNNL-12127, Pacific Northwest National Laboratories (PNNL), Richland, Washington.

Horton, D.G., B.A. Williams, and C.S. Cearlock, 2000. *Borehole Data Package for the 216-S-10 Pond and Ditch Well 299-W26-13*, PNNL-13198, Pacific Northwest National Laboratories (PNNL), Richland, Washington.

U.S. Department of Energy (DOE), 2000. *Hanford Tank Farms Vadose Zone, Seventh Recalibration of Spectral Gamma-Ray Logging Systems Used for Baseline Characterization Measurements in the Hanford Tank Farms,* GJO-2000-142-TAR, GJO-HAN-30, prepared by MACTEC-ERS for the Grand Junction Office, Grand Junction, Colorado.

__________, 2002. *Hanford Geophysical Logging Project, 2001 Recalibration of Logging Systems for Characterization of Subsurface Contamination at the Hanford Site,* GJO-2002-328-TAR, prepared by MACTEC-ERS for the Grand Junction Office, Grand Junction, Colorado.

__________, 2003a. *Hanford Geophysical Logging Project, Data Analysis Manual,* GJO-HGLP 1.6.3, Rev. 0, prepared by S.M. Stoller Corp. for the Grand Junction Office, Grand Junction, Colorado.

__________, 2003b. *Hanford Geophysical Logging Project, Logging System Operating Procedures,* GJO-HGLP 1.6.5, Rev. 0, prepared by S.M. Stoller Corp. for the Grand Junction Office, Grand Junction, Colorado.

__________, 2003c. *Hanford Geophysical Logging Project, Project Management Plan,* GJO-HGLP 1.6.2, Rev. 0, prepared by S.M. Stoller Corp. for the Grand Junction Office, Grand Junction, Colorado.

Appendix A
Gamma Energy and Yield Values for Prominent Gamma Lines Associated with Selected Radionuclides

	Z		A	E, keV	Y, %	HL, y
Pu-239	94	Pu	239	51.62	0.027	24110
Am-241	**95**	**Am**	**241**	**59.54**	**35.90**	**432.2**
Eu-155	63	Eu	155	60.01	1.13	4.7611
Sn-126	50	Sn	126	64.28	9.62	1.E+05
Np-237	91	Pa	233	75.35	1.39	2.14E+06
U-235	90	Th	231	84.21	6.60	7.04E+08
Th-232	90	Th	228	84.37	1.27	1.405E+10
Np-237	93	Np	237	86.48	12.40	2.14E+06
Eu-155	63	Eu	155	86.55	30.70	4.7611
Np-237	91	Pa	233	86.81	1.97	2.14E+06
Sn-126	50	Sn	126	86.94	8.92	1.E+05
Sn-126	50	Sn	126	87.57	37.00	1.E+05
U-238	90	Th	234	92.38	2.81	4.468E+09
U-238	90	Th	234	92.80	2.77	4.468E+09
Pu-239	93	Pu	239	98.78	0.0012	24110
Th-232	89	Ac	228	99.50	1.28	1.405E+10
Eu-155	**63**	**Eu**	**155**	**105.31**	**21.15**	**4.7611**
Eu-152	63	Eu	152	121.78	28.42	13.542
Eu-154	63	Eu	154	123.07	40.79	8.593
Th-232	89	Ac	228	129.07	2.45	1.405E+10
Pu-239	**93**	**Pu**	**239**	**129.30**	**0.0063**	**24110**
Ce-144	58	Ce	144	133.52	11.09	0.781
U-235	92	U	235	143.76	10.96	7.04E+08
U-235	92	U	235	163.33	5.08	7.04E+08
Sb-125	51	Sb	125	176.31	6.82	2.7582
U-235	**92**	**U**	**235**	**185.72**	**57.20**	**7.04E+08**
U-238	88	Ra	226	186.10	3.50	4.468E+09
U-235	92	U	235	202.11	1.08	7.04E+08
U-235	92	U	235	205.31	5.01	7.04E+08
Th-232	89	Ac	228	209.25	3.88	1.405E+10
Th-232	82	Pb	212	238.63	43.30	1.405E+10
Th-232	88	Ra	224	240.99	3.97	1.405E+10
U-238	82	Pb	214	241.98	7.50	4.468E+09
Eu-152	63	Eu	152	244.70	7.49	13.542
Th-232	89	Ac	228	270.24	3.43	1.405E+10
Th-232	81	Tl	208	277.36	2.25	1.405E+10
U-238	82	Pb	214	295.21	18.50	4.468E+09
Th-232	82	Pb	212	300.09	3.28	1.405E+10
Np-237	91	Pa	233	300.34	6.62	2.14E+06
Np-237	**91**	**Pa**	**233**	**312.17**	**38.60**	**2.14E+06**
Th-232	89	Ac	228	328.00	2.95	1.405E+10
Th-232	89	Ac	228	338.32	11.25	1.405E+10
Np-237	91	Pa	233	340.81	4.47	2.14E+06
Eu-152	**63**	**Eu**	**152**	**344.28**	**26.58**	**13.542**
U-238	82	Pb	214	351.92	35.80	4.468E+09
Pu-239	**93**	**Pu**	**239**	**375.05**	**0.0016**	**24110**
Sb-125	51	Sb	125	380.45	1.52	2.7582
Np-237	91	Pa	233	398.62	1.39	2.14E+06
Th-232	89	Ac	228	409.46	1.94	1.405E+10
Eu-152	63	Eu	152	411.12	2.23	13.542
Pu-239	**93**	**Pu**	**239**	**413.71**	**0.0015**	**24110**
Sn-126	**51**	**Sb**	**126**	**414.50**	**86.00**	**1.E+05**
Np-237	91	Pa	233	415.76	1.75	2.14E+06
Sb-125	**51**	**Sb**	**125**	**427.88**	**29.60**	**2.7582**
Eu-152	63	Eu	152	443.98	2.78	13.542
U-238	82	Pb	214	462.10	0.23	4.468E+09
Th-232	89	Ac	228	463.01	4.44	1.405E+10
Sb-125	51	Sb	125	463.37	10.49	2.7582
Th-232	89	Ac	228	508.96	0.47	1.405E+10
Th-232	81	Tl	208	510.77	8.06	1.405E+10
Ru-106	45	Rh	106	511.86	20.40	1.0238
Cs-134	55	Cs	134	563.23	8.38	2.062
Cs-134	55	Cs	134	569.32	15.43	2.062
Th-232	**81**	**Tl**	**208**	**583.19**	**30.11**	**1.405E+10**
Th-232	89	Ac	228	583.41	0.11	1.405E+10
Sb-125	51	Sb	125	600.60	17.86	2.7582
Cs-134	55	Cs	134	604.70	97.56	2.062
U-238	**83**	**Bi**	**214**	**609.31**	**44.79**	**4.468E+09**
Sn-126	51	Sb	126	620.00	1.55	1.E+05
Ru-106	45	Rh	106	621.93	9.93	1.0238
Sb-125	51	Sb	125	635.95	11.31	2.7582
Cs-137	**55**	**Cs**	**137**	**661.66**	**85.10**	**30.07**
U-238	83	Bi	214	665.45	1.29	4.468E+09
Sn-126	**51**	**Sb**	**126**	**666.10**	**86.00**	**1.E+05**
Sb-125	51	Sb	125	671.45	1.79	2.7582
Eu-154	63	Eu	154	692.43	1.80	8.593
Sn-126	**51**	**Sb**	**126**	**694.80**	**82.56**	**1.E+05**

	Z		A	E, keV	Y, %	HL, y
Ce-144	59	Pr	144	696.51	1.34	0.781
Eu-154	**63**	**Eu**	**154**	**723.31**	**20.22**	**8.593**
Th-232	89	Ac	228	726.86	0.64	1.405E+10
Th-232	83	Bi	212	727.33	6.58	1.405E+10
Th-232	89	Ac	228	755.32	1.01	1.405E+10
Eu-154	63	Eu	154	756.80	4.57	8.593
U-238p	91	Pa	234	766.36	0.29	4.468E+09
U-238	83	Bi	214	768.36	4.80	4.468E+09
Th-232	89	Ac	228	772.29	1.50	1.405E+10
Eu-152	63	Eu	152	778.90	12.96	13.542
Th-232	83	Bi	212	785.37	1.10	1.405E+10
U-238	82	Pb	214	785.91	0.85	4.468E+09
U-238	83	Bi	214	786.10	0.30	4.468E+09
Th-232	89	Ac	228	794.95	4.34	1.405E+10
Cs-134	55	Cs	134	795.85	85.44	2.062
Cs-134	55	Cs	134	801.93	8.73	2.062
U-238	83	Bi	214	806.17	1.12	4.468E+09
U-238p	91	Pa	234	811.00	0.51	4.468E+09
Th-232	89	Ac	228	835.71	1.68	1.405E+10
Mn-54	25	Mn	54	838.85	99.98	0.856
Th-232	81	Tl	208	860.56	4.43	1.405E+10
Eu-152	63	Eu	152	867.39	4.15	13.542
Eu-154	63	Eu	154	873.19	12.27	8.593
Th-232	89	Ac	228	911.21	26.60	1.405E+10
Sn-126	51	Sb	126	928.20	1.29	1.E+05
U-238	83	Bi	214	934.06	3.03	4.468E+09
U-238	83	Bi	214	964.08	0.38	4.468E+09
Eu-152	63	Eu	152	964.13	14.34	13.542
Th-232	89	Ac	228	964.77	5.11	1.405E+10
Th-232	89	Ac	228	968.97	16.17	1.405E+10
U-238p	**91**	**Pa**	**234**	**1001.03**	**0.84**	**4.468E+09**
Eu-154	63	Eu	154	1004.73	18.01	8.593
Sn-126	51	Sb	126	1034.90	1.81	1.E+05
Ru-106	45	Rh	106	1050.41	1.56	1.0238
Eu-152	63	Eu	152	1085.91	9.91	13.542
Eu-152	63	Eu	152	1089.70	1.71	13.542
Eu-152	63	Eu	152	1112.12	13.54	13.542
Zn-65	30	Zn	65	1115.55	50.60	0.669
U-238	83	Bi	214	1120.29	14.80	4.468E+09
U-238	83	Bi	214	1155.19	1.64	4.468E+09
Cs-134	55	Cs	134	1167.94	1.80	2.062
Co-60	**27**	**Co**	**60**	**1173.24**	**99.90**	**5.2714**
Eu-152	63	Eu	152	1212.95	1.40	13.542
U-238	83	Bi	214	1238.11	5.86	4.468E+09
Eu-154	**63**	**Eu**	**154**	**1274.44**	**35.19**	**8.593**
Na-22	11	Na	22	1274.53	99.94	2.609
Eu-152	63	Eu	152	1299.12	1.63	13.542
Co-60	**27**	**Co**	**60**	**1332.50**	**99.98**	**5.2714**
Cs-134	55	Cs	134	1365.15	3.04	2.062
U-238	83	Bi	214	1377.67	3.92	4.468E+09
U-238	83	Bi	214	1401.50	1.55	4.468E+09
U-238	83	Bi	214	1407.98	2.80	4.468E+09
Eu-152	**63**	**Eu**	**152**	**1408.01**	**20.87**	**13.542**
Th-232	89	Ac	228	1459.14	0.80	1.405E+10
K-40	**19**	**K**	**40**	**1460.83**	**10.67**	**1.277E+09**
U-238	83	Bi	214	1509.23	2.12	4.468E+09
Th-232	89	Ac	228	1588.21	3.27	1.405E+10
Eu-154	63	Eu	154	1596.50	1.80	8.593
Th-232	83	Bi	212	1620.50	1.49	1.405E+10
Th-232	89	Ac	228	1630.63	1.60	1.405E+10
U-238	83	Bi	214	1661.28	1.14	4.468E+09
U-238	83	Bi	214	1729.60	2.88	4.468E+09
U-238	**83**	**Bi**	**214**	**1764.49**	**15.36**	**4.468E+09**
U-238	83	Bi	214	1847.42	2.04	4.468E+09
U-238	83	Bi	214	2118.55	1.14	4.468E+09
U-238	83	Bi	214	2204.21	4.86	4.468E+09
U-238	83	Bi	214	2447.86	1.50	4.468E+09
Th-232	**81**	**Tl**	**208**	**2614.53**	**35.34**	**1.405E+10**

Notes: commonly used lines are in **boldface**
energy values are rounded to 2 decimal places
the most intense lines are shown
lines with yields < 1% are generally not shown

ref: Firestone & Shirley, 1996 Table of Isotopes
prepared by: RG McCain

11/15/02

	Z		A	E, keV	Y, %	HL, y
Na-22	11	Na	22	1274.53	99.94	2.609
Mn-54	25	Mn	54	838.85	99.98	0.856
Co-60	**27**	**Co**	**60**	**1332.50**	**99.98**	**5.2714**
Co-60	**27**	**Co**	**60**	**1173.24**	**99.90**	**5.2714**
Zn-65	30	Zn	65	1115.55	50.60	0.669
Ru-106	45	Rh	106	511.86	20.40	1.0238
Ru-106	45	Rh	106	621.93	9.93	1.0238
Ru-106	45	Rh	106	1050.41	1.56	1.0238
Sb-125	**51**	**Sb**	**125**	**427.88**	**29.60**	**2.7582**
Sb-125	51	Sb	125	600.60	17.86	2.7582
Sb-125	51	Sb	125	635.95	11.31	2.7582
Sb-125	51	Sb	125	463.37	10.49	2.7582
Sb-125	51	Sb	125	176.31	6.82	2.7582
Sb-125	51	Sb	125	671.45	1.79	2.7582
Sb-125	51	Sb	125	380.45	1.52	2.7582
Sn-126	**51**	**Sb**	**126**	**414.50**	**86.00**	**1.E+05**
Sn-126	**51**	**Sb**	**126**	**666.10**	**86.00**	**1.E+05**
Sn-126	**51**	**Sb**	**126**	**694.80**	**82.56**	**1.E+05**
Sn-126	50	Sn	126	87.57	37.00	1.E+05
Sn-126	50	Sn	126	64.28	9.62	1.E+05
Sn-126	50	Sn	126	86.94	8.92	1.E+05
Sn-126	51	Sb	126	1034.90	1.81	1.E+05
Sn-126	51	Sb	126	620.00	1.55	1.E+05
Sn-126	51	Sb	126	928.20	1.29	1.E+05
Cs-134	55	Cs	134	604.70	97.56	2.062
Cs-134	55	Cs	134	795.85	85.44	2.062
Cs-134	55	Cs	134	569.32	15.43	2.062
Cs-134	55	Cs	134	801.93	8.73	2.062
Cs-134	55	Cs	134	563.23	8.38	2.062
Cs-134	55	Cs	134	1365.15	3.04	2.062
Cs-134	55	Cs	134	1167.94	1.80	2.062
Cs-137	**55**	**Cs**	**137**	**661.66**	**85.10**	**30.07**
Ce-144	58	Ce	144	133.52	11.09	0.781
Ce-144	59	Pr	144	696.51	1.34	0.781
Eu-152	63	Eu	152	121.78	28.42	13.542
Eu-152	**63**	**Eu**	**152**	**344.28**	**26.58**	**13.542**
Eu-152	**63**	**Eu**	**152**	**1408.01**	**20.87**	**13.542**
Eu-152	63	Eu	152	964.13	14.34	13.542
Eu-152	63	Eu	152	1112.12	13.54	13.542
Eu-152	63	Eu	152	778.90	12.96	13.542
Eu-152	63	Eu	152	1085.91	9.91	13.542
Eu-152	63	Eu	152	244.70	7.49	13.542
Eu-152	63	Eu	152	867.39	4.15	13.542
Eu-152	63	Eu	152	443.98	2.78	13.542
Eu-152	63	Eu	152	411.12	2.23	13.542
Eu-152	63	Eu	152	1089.70	1.71	13.542
Eu-152	63	Eu	152	1299.12	1.63	13.542
Eu-152	63	Eu	152	1212.95	1.40	13.542
Eu-154	63	Eu	154	123.07	40.79	8.593
Eu-154	**63**	**Eu**	**154**	**1274.44**	**35.19**	**8.593**
Eu-154	**63**	**Eu**	**154**	**723.31**	**20.22**	**8.593**
Eu-154	63	Eu	154	1004.73	18.01	8.593
Eu-154	63	Eu	154	873.19	12.27	8.593
Eu-154	63	Eu	154	756.80	4.57	8.593
Eu-154	63	Eu	154	692.43	1.80	8.593
Eu-154	63	Eu	154	1596.50	1.80	8.593
Eu-155	63	Eu	155	86.55	30.70	4.7611
Eu-155	**63**	**Eu**	**155**	**105.31**	**21.15**	**4.7611**
Eu-155	63	Eu	155	60.01	1.13	4.7611
U-235	**92**	**U**	**235**	**185.72**	**57.20**	**7.04E+08**
U-235	92	U	235	143.76	10.96	7.04E+08
U-235	90	Th	231	84.21	6.60	7.04E+08
U-235	92	U	235	163.33	5.08	7.04E+08
U-235	92	U	235	205.31	5.01	7.04E+08
U-235	92	U	235	202.11	1.08	7.04E+08
Np-237	**91**	**Pa**	**233**	**312.17**	**38.60**	**2.14E+06**
Np-237	93	Np	237	86.48	12.40	2.14E+06
Np-237	91	Pa	233	300.34	6.62	2.14E+06
Np-237	91	Pa	233	340.81	4.47	2.14E+06
Np-237	91	Pa	233	86.81	1.97	2.14E+06
Np-237	91	Pa	233	415.76	1.75	2.14E+06
Np-237	91	Pa	233	75.35	1.39	2.14E+06
Np-237	91	Pa	233	398.62	1.39	2.14E+06
Pu-239	94	Pu	239	51.62	0.0271	24110
Pu-239	**93**	**Pu**	**239**	**129.30**	**0.0063**	**24110**
Pu-239	**93**	**Pu**	**239**	**375.05**	**0.0016**	**24110**
Pu-239	**93**	**Pu**	**239**	**413.71**	**0.0015**	**24110**
Pu-239	93	Pu	239	98.78	0.0012	24110
Am-241	**95**	**Am**	**241**	**59.54**	**35.90**	**432.2**

	Z		A	E, keV	Y, %	HL, y
K-40	**19**	**K**	**40**	**1460.83**	**10.67**	**1.277E+09**
Th-232	82	Pb	212	238.63	43.30	1.405E+10
Th-232	**81**	**Tl**	**208**	**2614.53**	**35.34**	**1.405E+10**
Th-232	**81**	**Tl**	**208**	**583.19**	**30.11**	**1.405E+10**
Th-232	89	Ac	228	911.21	26.60	1.405E+10
Th-232	89	Ac	228	968.97	16.17	1.405E+10
Th-232	89	Ac	228	338.32	11.25	1.405E+10
Th-232	81	Tl	208	510.77	8.06	1.405E+10
Th-232	83	Bi	212	727.33	6.58	1.405E+10
Th-232	89	Ac	228	964.77	5.11	1.405E+10
Th-232	89	Ac	228	463.01	4.44	1.405E+10
Th-232	81	Tl	208	860.56	4.43	1.405E+10
Th-232	89	Ac	228	794.95	4.34	1.405E+10
Th-232	88	Ra	224	240.99	3.97	1.405E+10
Th-232	89	Ac	228	209.25	3.88	1.405E+10
Th-232	89	Ac	228	270.24	3.43	1.405E+10
Th-232	82	Pb	212	300.09	3.28	1.405E+10
Th-232	89	Ac	228	1588.21	3.27	1.405E+10
Th-232	89	Ac	228	328.00	2.95	1.405E+10
Th-232	89	Ac	228	129.07	2.45	1.405E+10
Th-232	81	Tl	208	277.36	2.25	1.405E+10
Th-232	89	Ac	228	409.46	1.94	1.405E+10
Th-232	89	Ac	228	835.71	1.68	1.405E+10
Th-232	89	Ac	228	1630.63	1.60	1.405E+10
Th-232	89	Ac	228	772.29	1.50	1.405E+10
Th-232	83	Bi	212	1620.50	1.49	1.405E+10
Th-232	89	Ac	228	99.50	1.28	1.405E+10
Th-232	90	Th	228	84.37	1.27	1.405E+10
Th-232	83	Bi	212	785.37	1.10	1.405E+10
Th-232	89	Ac	228	755.32	1.01	1.405E+10
Th-232	89	Ac	228	1459.14	0.80	1.405E+10
Th-232	89	Ac	228	726.86	0.64	1.405E+10
Th-232	89	Ac	228	508.96	0.47	1.405E+10
Th-232	89	Ac	228	583.41	0.11	1.405E+10
U-238	**83**	**Bi**	**214**	**609.31**	**44.79**	**4.468E+09**
U-238	82	Pb	214	351.92	35.80	4.468E+09
U-238	82	Pb	214	295.21	18.50	4.468E+09
U-238	**83**	**Bi**	**214**	**1764.49**	**15.36**	**4.468E+09**
U-238	83	Bi	214	1120.29	14.80	4.468E+09
U-238	82	Pb	214	241.98	7.50	4.468E+09
U-238	83	Bi	214	1238.11	5.86	4.468E+09
U-238	83	Bi	214	2204.21	4.86	4.468E+09
U-238	83	Bi	214	768.36	4.80	4.468E+09
U-238	83	Bi	214	1377.67	3.92	4.468E+09
U-238	88	Ra	226	186.10	3.50	4.468E+09
U-238	83	Bi	214	934.06	3.03	4.468E+09
U-238	83	Bi	214	1729.60	2.88	4.468E+09
U-238	90	Th	234	92.38	2.81	4.468E+09
U-238	83	Bi	214	1407.98	2.80	4.468E+09
U-238	90	Th	234	92.80	2.77	4.468E+09
U-238	83	Bi	214	1509.23	2.12	4.468E+09
U-238	83	Bi	214	1847.42	2.04	4.468E+09
U-238	83	Bi	214	1155.19	1.64	4.468E+09
U-238	83	Bi	214	1401.50	1.55	4.468E+09
U-238	83	Bi	214	2447.86	1.50	4.468E+09
U-238	83	Bi	214	665.45	1.29	4.468E+09
U-238	83	Bi	214	1661.28	1.14	4.468E+09
U-238	83	Bi	214	2118.55	1.14	4.468E+09
U-238	83	Bi	214	806.17	1.12	4.468E+09
U-238	82	Pb	214	785.91	0.85	4.468E+09
U-238	83	Bi	214	964.08	0.38	4.468E+09
U-238	83	Bi	214	786.10	0.30	4.468E+09
U-238	82	Pb	214	462.10	0.23	4.468E+09
U-238p	**91**	**Pa**	**234**	**1001.03**	**0.84**	**4.468E+09**
U-238p	91	Pa	234	811.00	0.51	4.468E+09
U-238p	91	Pa	234	766.36	0.29	4.468E+09

Notes: commonly used lines are in **boldface**
energy values are rounded to 2 decimal places
the most intense lines are shown
lines with yields < 1% are generally not shown

ref: Firestone & Shirley, 1996 Table of Isotopes
prepared by: RG McCain

11/15/02